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The promotion of community energy projects in Chile and Scotland: an economic approach using biform games.

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A B S T R A C T

We model simple and novel three-player bi-form coalitional games to analyse community energy projects in Chile and Scotland. We take into account two methods based on biform games, which deal with games with a non-empty Core and an empty Core, respectively, and construct models based on real-world data on community energy projects, net billing (or distributed generation) schemes, and ordinary utility contracts. We then use these to derive insights about the economic-strategic viability of community energy projects, in the sense of stability within the projects or coalitions and competitiveness versus the other schemes. Under some mild assumptions, we find that community energy projects can be the best strategy to follow for residential electricity customers in Scotland and Chile. Cost subsidisation can further improve community energy incentives. Moreover, after a statistical simulation, we find that community energy projects present more opportunities to be implemented in comparison with net billing schemes in both countries. We use these results to draw conclusions for the community energy sector and show that biform games can be a valuable tool to analyse increasingly complex electricity markets.

Keywords: *Community Energy, Stochastic programming, Biform Games, Scotland, Chile*.

1. Introduction

Citizen participation in energy production is increasingly becoming an important matter in many countries around the world. This is evidenced by the fact that the number of news items, reports, scientific articles, dedicated public and private organisations, and projects that are related to or involved in this matter is steadily increasing. Moreover, this concept is also progressively playing a major role in governments' decisions, through a variety of public policies, laws and regulations that have been or are being implemented; an important example is article 16 on local energy communities in the European Union's electricity directive[1]. Unsurprisingly, the corresponding installed capacity of citizen-led electricity generation projects has increased remarkably during the last few years, especially in some European countries like Scotland [1-7]. There are other countries, like the Netherlands, Spain, and Sweden, which show similar trends. Additionally, Germany and Denmark deserve mention, as these countries represent a model to follow given the nature and number of projects and their contribution to the generation mix [8-10]. These experiences can be used to encourage and help other less developed countries, like Chile, in promoting and implementing their own citizen-led projects in energy generation. In fact, the Chilean Government has explicitly declared its willingness to support a more decentralised system and a higher participation of citizens in energy markets as prosumers, rather than mere customers [11,12].

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[1] See https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52016PC0864&from=EN

Under the broad umbrella of citizen participation in energy production, it is possible to find a wide variety of initiatives, such as community energy projects [13,14], distributed generation projects [15], locally-owned energy projects [16], projects based on hybrid partnerships (with public, private, and/or civil involvement) [10], among others. Of course, the diversity of projects will depend upon the specific context in each country or energy market.

For the purposes of this paper, the focus will be on the emergence of community energy projects in Scotland and Chile. These initiatives are examined and contrasted, in the sense of economic-strategic viability, with other well-known schemes; specifically, net billing (or distributed generation) projects, and regular utility contracts. Economic-strategic viability means that an initiative or project provides the best possible payoff or outcome for the incumbents, given a feasible and rational strategy or set of actions. We recognise that there are other elements that might affect people's decisions and/or behaviour related to the community energy emergence, such as psychological, sociological, legal, political, historical or environmental factors. These could be included in more realistic models, at a price of reducing model transparency and increasing computational cost. We therefore focus exclusively on the economic-strategic side of community energy initiatives. The best possible payoff or outcome can measured in terms of either monetary losses or benefits, depending on the circumstances. To be economic-strategically viable, community energy projects should guarantee to their members proper cooperation mechanisms and attractive incentives to join and remain a part of the project. Moreover, community energy projects should themselves be competitive compared to other ways of energy production, which implies offering higher benefits for their members, as well as a long-term sustainability. These characteristics imply a dual behaviour of community energy projects because, on the one hand, these projects need cooperation and, on the other hand, these initiatives need to compete with others projects. As far as we are aware, there are no existing studies that model such dual behaviour from an economic-strategic perspective.

To derive insights about the stability inside projects (or coalitions) and competitiveness with other schemes, which can help policy makers encourage a thriving community energy sector through proper long-term public policies that are compatible with the energy market incumbents' incentives, we therefore need new modelling frameworks. We use methods from game theory to analyse this setting. Game theory can be defined as a discipline that aims at determining the best possible outcome and the corresponding strategy (or set of actions) to get this outcome, for a number of decision-makers (players) who interact in a particular situation or context (game). Game theory also allows finding out what the players' incentives are and whether they are aligned and affected by any stimulus that might imply changes (instability). In principle, games can be cooperative, where players cooperate with each other, and non-cooperative, where players do not cooperate but make their decisions individually to maximise their own benefits. There are also hybrid games, which consider cooperative and non-cooperative behaviour at the same time. Although these have not been applied to energy markets, to our best knowledge, we claim that they are especially appropriate to model the dual behaviour of community energy initiatives. In this vein, there exists a variety of hybrid games, however, this paper is focused on a simple and intuitive approach called biform games [17,18], which, as we will show, can be applied to electricity markets and the community energy sector.

Adapting the existing literature, we therefore develop a specific application of biform games to the community energy emergence in Scotland and Chile, by formulating simple and novel three-player games. In these games, there exist two residential electricity consumers and a distributor or supplier, who provides electricity to both consumers. The residential electricity consumers might be involved in energy production by participating in either a net billing (or distributed generation) scheme or a community energy project. There are therefore two decisional components in this problem that are addressed by using biform games: a non-cooperative component related to being involved in electricity generation and a cooperative component related to the payoff distribution within a certain coalition or energy production initiative. Through the solution to these games, we aim at answering, from an economic-strategic perspective, the following research questions: a) are community energy projects a viable way of producing energy for residential customers?; and b) are community energy projects, in terms of providing the best possible payoff for residential customers, more competitive than other projects?

Thus, this paper presents three contributions. First, this work provides a novel set of methods to quantify the economic-strategic viability of the community energy sector and the interaction with other projects or schemes, where most previous research focuses on qualitative methods. Second, we derive some lessons that can help people distribute a payoff or outcome among the members of a community energy project. Third, this paper is based on a methodology that is not currently widely used for the analysis of electricity markets and the community energy sector. We note that, since we are mainly concerned with demonstrating a new method and deriving qualitative insights, our models are highly simplified and we make a number of restrictive assumptions.

The remainder of this paper is organised as follows. In section 2, we present the theoretical background necessary to build up the biform games. In section 3, we reveal the main features and assumptions of our approach based on biform games. In section 4, the results are shown. In section 5, a discussion of those results is given. Finally, section 6 concludes.

2. Theoretical background

2.1 State-of-the-art analysis of the community energy emergence

A community energy project implies cooperation among the members, which is particularly crucial. People with different feelings, motivations, attitudes, judgement, professional background and experience, points of view, etc. [19-26], need to agree with others in order to successfully carry out and implement the project. Many studies show the importance of the social-institutional elements in the emergence, constitution, and operation of community energy projects [14,19-22,27-35]. Additionally, because these initiatives are currently playing a role within liberalised electricity/energy markets, other studies characterise the (potential) incumbents of the community energy sector, as well as the market and its characteristics [9,23-26,36-43].

Fewer studies focus specifically on economic-financial aspects. In one study, Leontief's Input-Output Model is applied to Scottish community energy projects to evaluate their impacts on the local economy [44]. Lakshmi & Tilley [45] determine the Return on Stakeholders' Capital (RoSC) and Cost of Stakeholders' capital (CoSC) for a particular community energy project in England, for the purpose of monitoring and improving its functioning, regardless the scale. Berka et al. [46] calculate the expected Net Present Value (NPV) and Levelized Cost of Energy (LCOE) for community-owned projects at different development stages, and show the existence of higher costs, longer project development times, and higher risks, in comparison with commercial projects.

In relation to the economic-strategic viability of projects, Abada et al. [47] analyse an energy community, understood as an initiative where several households in a given building decide to use a single meter and potentially cooperate and install solar photovoltaics (PV) panels. They point out that there is no assurance that coalitions of households will be viable and that this is affected by the installation costs, coordination costs, and sharing rules. Lo Prete & Hobbs [48] show how microgrid development affects costs and benefits for network incumbents (a utility company, a private investor in microgrids, and residential customers), highlighting market failures, the importance of microgrid introduction timing, and effects on prices. Lee et al. [49] analyse the cooperation between small-scale electricity suppliers and end-users in direct trading, proposing a fair pricing and revenue division scheme for them. There are also other studies that propose resources allocation schemes in different contexts [50-53]. More recently, Abada et al. [54] highlight the interaction between energy communities and a distribution system operator and the effects derived from the grid tariff structure.

Hence, it seems that the prevailing trend has been to analyse the social-institutional features of community energy projects, principally dealing with psychological, sociological, historical, institutional, and/or political factors, in order to find out which category or categories significantly affects the emergence and success of community energy projects. Consequently, we can find relevant information about people's attitudes and willingness towards community energy projects, the impact derived from particular public policies, the features of such projects that might help to clearly define community energy, and so on. Most of the aforementioned studies use statistical and social sciences techniques. On the other hand, the economic-financial side of the community energy emergence has received less attention, which indicates an opportunity to properly delve into this matter, for instance, by developing more advanced valuation models of such projects, new ways of funding, more knowledge about a suitable cash flow management, etc. Concerning the last group of studies related to the economic-strategic viability, it is important to highlight two elements of interest: firstly, most of these studies are based on cooperative game theory, where in essence players form coalitions to get the best possible payoff or outcome and distribute it among them, ensuring stability. The basic idea is then assuring that the members will remain in the coalition. Competition between community energy projects and other existing schemes is not considered in these studies. Secondly, these investigations take into account projects that are closer to or under the above-mentioned concept of distributed generation than that of community energy, mainly because the focus is on specific buildings and/or dwellings within these, rather than proper small or medium-scale power plants owned by communities. Also, the strategic interactions chiefly occur at the distribution level. This is not a sine qua non condition for community energy projects.

Thus, from our perspective, there is a gap that deserves to be appropriately explored in terms of modelling community energy projects and their interactions with other schemes or projects, in order to find clues that may help to answer the research questions mentioned above.

2.2 Biform games fundamentals

Community energy projects present a dual behaviour: cooperative on one side, where the members of a community energy project need to cooperate with each other in order to carry out the initiative; and non-cooperative on the other, where the project itself competes with other projects or schemes of electricity/energy provision. As mentioned above, such dual behaviour can be modelled by using hybrid games. Examples of hybrid games and their variety of applications can be found in several studies [55-58]. Within the hybrid game theory literature, biform games form a specific category. A biform game [17] consists of a hybrid game (cooperative and non-cooperative) that employs the Core (second game stage) and Nash equilibrium (first game stage) as solution mechanisms, which are developed under a common methodology. The link between both stages is represented by a confidence index, which is derived from the Hurwicz criterion and subsequent modifications [17,59,60]. Accordingly, a biform game can be formally defined as follows [17]:

$$(Z_i, \dots, Z_n; V; \alpha_i, \dots, \alpha_n) \quad (1)$$

Where:

Z_i is a finite strategy set for each $i = 1, \dots, n$ player
z_i is the player i's selected strategy
V is a map from $Z_i \times \dots \times Z_n$ to the set of maps $P(I) \rightarrow \mathbb{R}$, with $V(z_i, \dots, z_n)(\emptyset) = 0$ for every $z_i, \dots, z_n \in Z_i \times \dots \times Z_n$.
α_i is the player i's confidence index, which is between 0 and 1.

The resulting set of strategies $z_i, \dots, z_n \in Z_i \times \dots \times Z_n$ defines a transferable utility game with characteristic function $V(z_i, \dots, z_n)$: $P(I) \rightarrow \mathbb{R}$, where $P(I)$ is the set of all subsets of the players set I. This means that, for each coalition $S \subseteq I$, $V(z_i, \dots, z_n)(S)$ is the value created by coalition S, given that the players choose the strategies $z_i, \dots, z_n$. Thus, to solve a biform game, it is necessary to follow five steps according to Branderburger & Stuart [17]:

a) Determine the Core for the cooperative part or second stage of the (biform) game.
b) Calculate the range of payoffs for each player.
c) Use α_i and $(1-\alpha_i)$ to compute the weighted average in order to evaluate the cooperative part of the game, applying that index to the largest and smallest payoffs that every player could receive.
d) Assign to player i a payoff equal to the i's weighted average, in order to reduce the cooperative stage to a non-cooperative game.
e) Compute the Nash equilibrium of the non-cooperative part or first stage of the game.

Biform games have been applied to a wide range of economic and strategic problems where outcomes are influenced by both co-operation and competition [61-70]. In this sense, it is worth highlighting the flexibility that biform games can provide in terms of (potential) applications, which might help to deal with different situations where is possible to find cooperation and competition at the same time. This is also related to other disciplines such as engineering, as particularly developed in [66]. Given this flexibility, biform games allow obtaining deeper knowledge about stability, or how a community-led project can incentivise and retain the membership, by giving information about the players' negotiation power that comes from the cooperative stage of each game without considering procedural assumptions of bargaining. In addition, through the non-cooperative stage, it is possible to get information about whether a strategy is good and creates a favourable cooperative stage for players, where they have the chance to negotiate and then obtain the best possible payoff or outcome [17]. All of this might help to better understand the emergence of community energy projects, as well as the related cooperation mechanisms and competitiveness of such projects, which can be translated into economic-strategic viability.

Biform games take into account the Nash equilibrium as the solution mechanism for the first (non-cooperative) stage, which is defined as follows: the strategies $(z_i^*, \dots, z_n^*)$ are Nash Equilibria if, for each player i, z_i^* is player i's best response to the strategies $(z_1^*, \dots, z_{i-1}^*, z_{i+1}^*, \dots, z_n^*)$ chosen by the other players that solves the following optimisation problem [71]:

$$max_{z_i \in Z_i} f_i(z_1^*, \dots, z_{i-1}^*, z_i^*, z_{i+1}^*, \dots, z_n^*) \tag{2}$$

The function payoff, f_i, is given by the cooperative part or second stage of the game. To solve it, biform games take into account the Core as the solution mechanism. The Core is defined as follows [72,73]:

$$C(v) = \{x \in \mathbb{R}^n \mid \sum_{i \in I} x_i = v(I), \sum_{i \in S} x_i \geq v(S) \; \forall \; S \in P(I)\} \tag{3}$$

In words, the Core can be defined as a mathematical methodology to distribute payoffs or outcomes among the players, in which the sum of all payoffs of each player i ($\sum_{i \in I} x_i$), who belong to the players set I (also referred as grand coalition), has to be equal to the coalitional value of I, $v(I)$, represented by a characteristic function v. This is called the efficiency principle. Additionally, the sum of all payoffs of each player i who belong to coalition S ($\sum_{i \in S} x_i$), has to be greater than or equal to the coalitional value of S, $v(S)$. This is called coalitional rationality. This applies to all coalitions that belong to the coalition set $P(I)$. Consequently, any payoff allocation or distribution agreement under the Core is stable, in the sense that no player can achieve a higher payoff outside a coalition within the Core [73]. Mathematically, the Core can be non-empty (feasible solution) or empty (infeasible solution), as shown in Fig. 1.

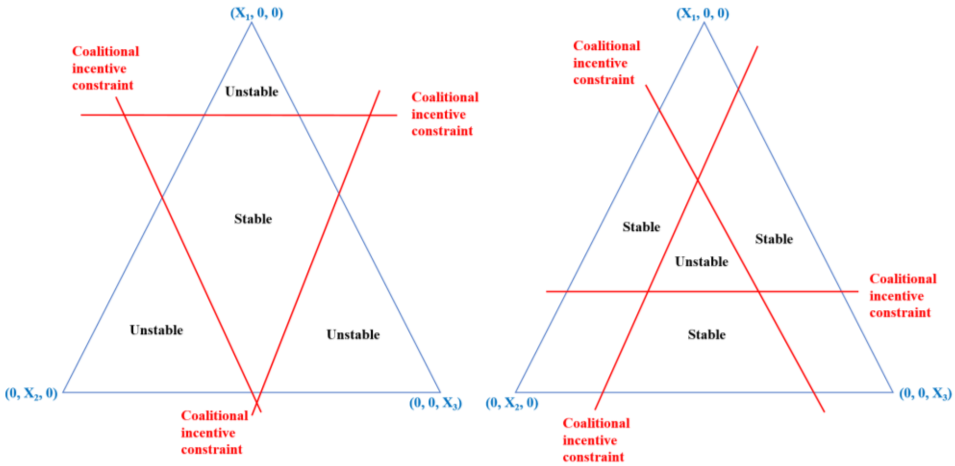

Fig. 1. Non-empty and empty Core (adapted from [74])

Fig. 1 represents a way to plot the Core by drawing a triangle in barycentric coordinates[2], in which the plane of the plot is $\sum_{i \in I} x_i = v(I)$ and drawing each point on the plane at which the three coordinates sum to $v(I)$. Then, the coalitional incentives constraints are drawn on the plane, in order to find which points are stable or unstable. Moreover, to find games with an appropriate and feasible solution, the Core has to meet three mathematical conditions at the same time, according to the Bondareva-Shapley theorem: superadditivity, convexity, and balancedness [73-76].

The link between the first and second stages of the biform game is the parameter α_i, which is the player i's confidence index. This index can be seen as a representation of the players' beliefs about the fraction of the coalitional value they could capture in the cooperative part of the game. We can therefore obtain information about the degree of competition and potential bargaining opportunities. This is why the confidence index is applied to the largest and smallest payoffs that every player could receive once the Core is determined. A confidence index near one means an optimistic player who expects to capture most of the value to be distributed in the second stage, whereas a confidence index close to zero means the opposite [17].

Recalling that the Core can be non-empty or empty, we also have to deal with games that have an empty Core. Summerfield & Dror [18] develop a methodology that treats a biform game as a two-stage stochastic programming problem with recourse, which deals with either empty or non-empty Core games. This methodology is defined as follows:

$$f_i(z_i^*, z_j^*, z_k^*) = max_{z_i \in \{0,1\}} - c^1(z_i) + Q_i(z_i, z_j, z_k) \tag{4}$$

where:

$$Q_i(z_i, z_j, z_k) = max_{T \subseteq \{i,j,k\}} \, \alpha_i \overline{x_i}^{T,(z_i, z_j, z_k)} + (1 - \alpha_i) \underline{x_i}^{T,(z_i, z_j, z_k)} \tag{5}$$

$s.t.$

$$C(T, v) \neq \emptyset \tag{6}$$

Here, players $i, j, k \in I$ and $i \neq j \neq k$. Furthermore, $T \subseteq P(I)$ represents a stable subcoalition with a non-empty Core (in the second stage or cooperative part of the game) that maximises player i's expected payoff. That is, a coalitional game $\Gamma = (I, v)$ will be a subgame $\Gamma = (T, v)$ with $\emptyset \neq T \subseteq P(I)$, so T can be now also be treated as a coalition. It is important to notice that all coalitional values based on T are equal to those based on I. The players' decisions in the non-cooperative part or first stage

[2] See http://mathworld.wolfram.com/BarycentricCoordinates.html

of the game are represented by $z_i \in \{0, 1\}$. The term $-c^1(z_i)$ denotes a decision cost during the first stage, derived from the second stage symbolised by $Q_i(z_i, z_j, z_k)$. $\overline{x_i}$ and $\underline{x_i}$ represent the upper and lower payments, respectively, that a particular player could receive. We consider this approach for games with an empty Core.

3. An application of biform games to the community energy sector

3.1 Framework

In this section, a specific application of biform games to the community energy sector is formulated to better understand this phenomenon from an economic-strategic perspective. Bearing in mind the concepts shown above, the assumptions for this applied model are as follows.

We consider two residential electricity customers, who have the option to participate in energy production using solar photovoltaic (PV) technology in one of following two ways:

a) The first way to do so is through a net billing (or distributed generation) scheme, jointly carried out with a distributor or supplier as is usual in several countries (including Chile and the UK), in which customers can individually buy (rooftop) solar PV panels and the energy injection to the grid is valued at an injection rate that is different from the consumption rate. The resulting monetary value is then subtracted from the energy consumption expenses [12]. Accordingly, this type of project can be catalogued under the Ackermann et al.'s [15] definition, which defines distributed generation as "an electric power source connected directly to the distribution network or on the customer site of the meter".

b) The other way is having an agreement only between both residential electricity customers to build and set up a small-scale solar PV power plant, which is conceived to satisfy their electricity consumption. We consider the case of implementing an initiative for self-consumption only for simplicity. Accordingly, this project can be catalogued under the Fuentes González et al.'s [12] definition, which defines community energy projects as "projects conceived, carried out, and implemented by people who are:

- Interested in generating energy
- Located close to or in the exact place of the project
- Well-organised under any suitable legal and organisational structure
- The owner, or have a high participation in the ownership, of the project
- The main (and/or the first) beneficiary of the project
- Primarily interested in welfare maximisation and income generation."

It is important to note that the same authors notice that community energy projects are more complex than distributed generation ones, in terms of their nature and characteristics, because the former do not need to be connected to distribution networks, can involve more than one customer at the same time, and imply not only technical aspects, but also social and economic ones [12].

On the other hand, if the residential electricity customers decide not to participate in energy production, they can maintain a regular (ordinary) electricity provision scheme from a distributor or supplier.

Hence, these three modalities of participation in the electricity market constitute the three scenarios taken into account in our games: distributed generation scenario, community energy scenario, and base scenario, respectively. We then assume that all players perfectly know the costs, tariffs, rights, and obligations derived from their relations with other players in these three scenarios.

We model the aforementioned situation as three-player (coalitional) games with transferable utility. The cooperation agreements are negotiated by the players and can be enforced by some outside party, if necessary. The games can then be defined as follows:

$$\Gamma = (I, v) \tag{7}$$

Where:

Γ = a three-player (coalitional) cooperative game.
$I = \{1,2,3\}$ = the players set or grand coalition;
v = a function $P(I) \rightarrow \mathbb{R}$, with $v(\emptyset) = 0$, which indicates the maximal aggregate payoff of a coalition $S \in P(I)$;
$P(I)$ = set of coalitions (i.e., the set of all subsets of I). Additionally, I, $\emptyset$, and the single player sets $\{i\}$ (with $i \in I$), are treated as coalitions. Any payoff vector for n players is denoted as $x = (x_1, x_2 \dots x_n) \in \mathbb{R}^n$.

We therefore examine the three scenarios for each country (Scotland and Chile), as noted below in Table 1.

Table 1
Details of scenarios developed in each country

Relation / Scenario	Base scenario	Distributed generation scenario	Community energy scenario
Players involved	Player 1 & Player 3 Player 2 & Player 3	Player 1 & Player 3 Player 2 & Player 3	Player 1 & Player 2
Type of relation or agreement	Utility contract	Net billing scheme	Project through a legal organisation for self-consumption
Coalitions	$\{1,3\},\{2,3\}$	$\{1,2,3\}$	$\{1,2\}$

3.2 Key definitions and assumptions for payments and coalitional values

To determine the payments for each player and the corresponding coalitional values[3], we formulate the following equations:

a) Annual customers' electricity consumption payments at present value, $APPV_C$.

$$APPV_C = [(Dt_C \times AAC_C)/r][1 - 1/(1+r)^t] \quad \text{(USD/year)} \tag{8}$$

b) Annual distributor's/supplier's requirements payments at present value, $APPV_D$.

$$APPV_D = APPV_C\,(1 - \omega) \quad \text{(USD/year)} \tag{9}$$

c) Annual generation payment obtained by customers at present value, $AGPV_C$.

$$AGPV_C = [(GT_C \times AAG_C)/r][1 - 1/(1+r)^t] \quad \text{(USD/year)} \tag{10}$$

[3] The exchange rates considered for all calculations are USD/CLP 619.6 and USD/GBP 0.758 according to OANDA.com.

Where:

Dt_C= Distribution or supply tariff paid by customers.

AAC_C= Customers' annual average consumption.

GT_C = Generation tariff received by customers.

AAG_C = Customers' annual average generation.

ω = Added value generated and captured by the distributor/supplier, between 0 and 1.

r = Discount rate.

t = Period of time, in years.

Regarding the parameter Dt_C, we take into consideration representative tariffs from one of the main distributors/suppliers in each country, as shown in Table 2.

Table 2
Representative electricity tariffs assigned to customers in Chile[4] and Scotland[5]

Data / Country	Chile	Scotland	Unit
Chilean Tariff	90.71		CLP/kWh
British Tariff		14.03	p/kWh
Tariffs in USD	0.15	0.19	USD/kWh

Sources: [77,78]

The term AAC_C is defined according to the following criteria:

a) For player 1, we assume this player consumes 1,800 kWh/year in Chile [79] and 3,505 kWh/year in the UK [80], as we recognise this player as a residential low-middle income consumer of electricity.
b) For player 2, we assume this player consumes 7,865 kWh/year in Chile [79] and 4,972 kWh/year in the UK [80], as we recognise this player as a residential high income consumer of electricity.
c) It is important to notice that player 3 is a distributor (in Chile) or supplier (in Scotland) of electricity.

Concerning the term GT_C, we consider that players 1 and 2 have access to a sale (generation) rate of 0.10 USD/kWh [78] and 0.05 USD/kWh [81] in Chile and Scotland, respectively.

We parameterise AAG_C considering information about the potential generation of solar PV panels in Chile and Scotland. For the Scottish case, we take data from the Energy Saving Trust's Solar Energy Calculator considering as the consumer's location the city of Edinburgh, a roof slope of 45°, a shading less than 20% of the sky, with a southeast direction of the roof, and a medium installation size. The potential generation derived from the use of solar PV panels and corresponding costs are shown in Table 3.

Table 3
Potential generation derived from solar PV panels use and the related costs in Chile and Scotland

Criteria / Country	Chile	Scotland
Main location	Santiago	Edinburgh
Installed capacity	2 kWp	2 kWp
Potential annual generation	3,000 kWh	1,520 kWh
Cost (Local currency)	CLP 3,390,000	GBP 4,000
Solar PV Cost (USD)	5,471.27	5,277.05

Sources: [82,83]

[4] Valid at September 2017, considering the BT1 tariff including energy, capacity buying, distribution capacity, pool coordination and transmission use.
[5] Valid at September 2017, considering a simple average of all locations of British Gas Standard domestic single rate electricity for Direct Debit payment, with effect from 15-09-2017.

In order to determine the overnight capital cost $OCC_{per\ household}$, and then estimate the cost per household of a solar PV power plant in a community energy project which meets the capital requirements, we consider an $OCC_{per\ household}$ of 2,020 USD/kW and a capacity factor of 0.2 [84]. Moreover, we take the number of residential electricity customers of one municipality/council in each country, where we can find similar features for both residential customers. The selected places are Lo Barnechea for Chile, and The City of Edinburgh Council for Scotland, which have 364,868 customers [85] and 241,433 customers [86], respectively. In the Scottish case, it is important to note that we assume that each separate dwelling is a separate residential electricity customer. Furthermore, for practical purposes, and because it would be unrealistic to think that everyone could participate in this kind of initiative at the same time in a certain place, we just take a small proportion of those customers (0.1%) as potential participants. We assume that a half of them are low-middle income customers (player 1) and the rest are high income customers (player 2). The calculation details related to $OCC_{per\ household}$ for each country, are summarized in Table 4.

Table 4
Overnight Capital Cost (OCC) per household

Item / Specific Location	Lo Barnechea Municipality	City of Edinburgh Council	Unit
Selected customers	365	241	
Customers as player 1	182	121	
Customers as player 2	182	121	
Consumption player 1	328,381	423,111	kWh/yr
Consumption player 2	1,434,843	600,202	kWh/yr
Required capacity player 1	187	242	kW
Required capacity player 2	819	343	kW
Total required capacity	1,006	584	kW
OCC player 1	378,613	487,834	USD
OCC player 2	1,654,329	692,014	USD
$OCC_{per\ household}$ player 1	2,075	4,041	USD
$OCC_{per\ household}$ player 2	9,068	5,733	USD

The term ω is quantified by considering information from distributor's financial statements from 2012 to 2016, in order to have a representative measure of the value generated and captured by player 3, after receiving payments from players 1 and 2, and paying player 3's suppliers. We set ω to the average operating margin, defined as operating profit divided by revenues due to the core activities; 13% [87] and 5% [88] for the Chilean and Scottish case, respectively.

We use a discount rate r =10% and consider a 25-year horizon, which is the approximate useful life of solar PV panels [89]. Using these parameters, we bring all financial payments to their present value assuming a uniform time horizon.

Considering equations (8) to (10) and all the information shown above, the payments for each player are based given by the following equations:

Table 5
Formulas to compute the payments for each player in every scenario

	Base scenario	Distributed generation scenario	Community energy scenario
Player 1	(8)	$(10) - [(8) + \text{Solar PV Cost}]$	$(8) - OCC_{per\ household}$
Player 2	(8)	$(10) - [(8) + \text{Solar PV Cost}]$	$(8) - OCC_{per\ household}$
Player 3	$(8) - (9)$	Chilean case: $[(8) - (10) + \text{Solar PV Cost}] - \{[((8) - (10)) \times (1 - \omega)] + [(\text{Solar PV Cost}) \times (1\text{-}30\%)]\}$ Scottish case: $[(8) - (10)] - \{[((8) - (10)) \times (1 - \omega)]\}$	0

Table 5 lists the nature of all payments for each player, under the three scenarios described above. Accordingly, the payments under the base scenario represent how much players 1 and 2 pay for their electricity consumption to the distributor or supplier, which is simultaneously the amount that the latter receives, minus the corresponding costs based on the specified profit. The payments under the distributed generation scenario represent how much players 1 and 2 receive for the energy production from their solar PV panels, minus their electricity consumption and solar PV panel investment costs. At the same time, player 3 receives payments for the residential customers' consumption, minus their solar PV generation, and the corresponding costs based on a specific margin. It is worth nothing that, in Chile, players 1 and 2 can buy solar PV panels from distribution companies (we assume that the distributor's profit margin on solar panel sales is 30%) and specialised vendors, unlike in Scotland, where customers can only buy them from specialized vendors[6]. These differences are reflected in the corresponding formulas. The payments for the community energy scenario imply that players 1 and 2 receive the savings derived from their reduction in electricity consumption payments to the supplier or, alternatively, that the community-led project receives electricity payments, minus a lump-sum cost per player or household which represents their share in the project.

Assuming that the costs of solar PV panels and OCC are covered in just one instalment, we calculate the payments for each player, scenario, and country, taking into account all equations from Table 5, as shown in Tables 6 and 7.

Table 6
Payments received by every player and scenario in the Chilean case (amounts in USD)

Payments per player / Scenarios			Base scenario	Distributed generation scenario	Community energy scenario
Positive payments	Players	1	-	2,723.11	2,450.80
		2	-	2,723.11	10,708.64
		3	13,159.44	18,655.75	-
Negative payments	Players	1	-2,450.80	-7,922.07	-2,075.34
		2	-10,708.64	-16,179.91	-9,068.09
		3	-11,448.71	-14,370.27	-
Final payments	Players	1	-	-	375.46
		2	-	-	1,640.54
		3	1,710.73	4,285.48	-

Table 7
Payments received by every player and scenario in the Scottish case (amounts in USD)

Payments per player / Scenarios			Base scenario	Distributed generation scenario	Community energy scenario
Positive payments	Players	1	-	689.86	6,044.85
		2	-	689.86	8,574.90
		3	14,619.75	13,240.04	-
Negative payments	Players	1	-6,044.85	-11,321.90	-4,041.15
		2	-8,574.90	-13,851.94	-5,732.56
		3	-13,888.77	-12,578.04	-
Final payments	Players	1	-	-	2,003.70
		2	-	-	2,842.34
		3	730.99	662	-

Because the Core is considered within the concept of biform games, we clip all negative payments to zero. We therefore define all coalitions and their values, considering the data shown in Tables 6 and 7, in order to compute and solve the games presented in Tables 8 and 9, as shown below.

Table 8
Game 1 - Coalitions and their values for each scenario in the Chilean case (amounts in thousands of USD, which come from Table 6)

Coalitions / scenarios	No relation among the players	Base scenario	Distributed generation scenario	Community energy scenario
$\{\emptyset\}$	0			
$\{1\}$	0			
$\{2\}$	0			
$\{3\}$	0			
$\{1,2\}$				2.02
$\{1,3\}$		0.32		
$\{2,3\}$		1.39		
$\{1,2,3\}$			4.29	

Table 9
Game 2 - Coalitions and their values for each scenario in the Scottish case (amounts in thousands of USD, which come from Table 7)

Coalitions / scenarios	No relation among the players	Base scenario	Distributed generation scenario	Community energy scenario
$\{\emptyset\}$	0			
$\{1\}$	0			
$\{2\}$	0			
$\{3\}$	0			
$\{1,2\}$				4.85
$\{1,3\}$		0.30		
$\{2,3\}$		0.43		
$\{1,2,3\}$			0.66	

[6] The cost of solar PV panels is taken as an average of the values listed in http://www.theecoexperts.co.uk/how-much-do-solar-panels-cost-uk#/3 for devices of 2 kWp of installed capacity.

In these two tables, the sum of the values associated to coalitions $\{1,3\}$ and $\{2,3\}$ are equal to the final payment for player 3 in the base scenario in Tables 6 and 7. There are two terms in that sum, which correspond to player 1's and player 2's value under coalition with player 3 separately, according to the nature of the base scenario.

As a sensitivity analysis, we now modify the values in Tables 8 and 9 to clearly see the effects of cost subsidisation on the confidence indexes and Nash equilibria. For simplicity, we consider a support scheme in which solar PV panel costs and OCC are covered by annualised payments, mostly made by a subsidising entity, such as a government. Specifically, we consider a case in which consumers make only one payment in the first year of the project, after which the government pays the rest[7]. This implies that the payments series occur during the solar PV panels useful life mentioned before. In relation to the distributed generation scenario, we also now consider that solar PV panels are bought from specialised vendors in both countries. This means that, for the Chilean case, consumers can buy solar PV panels at a 50% lower cost.

The games and their corresponding coalitional values for this sensitivity analysis are shown in Tables 10 and 11.

Table 10
Game 3 - Coalitions and their values for each scenario in the Chilean case (amounts in thousands of USD)

Coalitions / scenarios	No relation among the players	Base scenario	Distributed generation scenario	Community energy scenario
$\{\emptyset\}$	0			
$\{1\}$	0			
$\{2\}$	0			
$\{3\}$	0			
$\{1,2\}$				11.93
$\{1,3\}$		0.32		
$\{2,3\}$		1.39		
$\{1,2,3\}$			1.00	

Table 11
Game 4 - Coalitions and their values for each scenario in the Scottish case (amounts in thousands of USD)

Coalitions / scenarios	No relation among the players	Base scenario	Distributed generation scenario	Community energy scenario
$\{\emptyset\}$	0			
$\{1\}$	0			
$\{2\}$	0			
$\{3\}$	0			
$\{1,2\}$				13.54
$\{1,3\}$		0.30		
$\{2,3\}$		0.43		
$\{1,2,3\}$			0.66	

In Tables 10 and 11, as before, the sum of the values associated to coalitions $\{1,3\}$ and $\{2,3\}$ are equal to the final payment for player 3 in the base scenario.

3.3 Procedural considerations

In all these three-player games there are two components of decisions: a non-cooperative and a cooperative one. The non-cooperative component represents an individual decision to get involved in an electricity generation project or simply buy electricity through a standard supply agreement. The cooperative component represents the possible payoffs and their distribution among the players who have decided to become involved in energy production. This involves negotiation power implications, as mentioned before. Consequently, given that we need to calculate the Core to solve the cooperative part of each game, we consider a triangle with barycentric coordinates, following the next inequality:

$$v(\{i,j,k\}) - x_k \geq v(\{i,j\}) \tag{11}$$

$$x_k \leq v(\{i,j,k\}) - v(\{i,j\}) \tag{12}$$

[7] Alternatively, once could find an equivalent investment cost subsidy that would give the same solution; for simplicity, we do not consider this.

With $i \neq j \neq k$ and $i, j, k \in I$

Then:

$$C(v) = \{x_i, x_j, x_k \in \mathbb{R}^3 : x_i + x_j + x_k = v(\{i,j,k\}), v(\{i\}) \leq x_i \leq v(\{i,j,k\}) - v(\{j,k\}), v(\{j\}) \leq x_j \leq v(\{i,j,k\}) - v(\{i,k\}), v(\{k\}) \leq x_k \leq v(\{i,j,k\}) - v(\{i,j\})\} \tag{13}$$

Apart from the considerations related to the calculation of the Core, it is important to verify whether the Core is non-empty or empty. To do so, we take into account the following inequalities which have to be met at the same time, according to the Bondareva-Shapley theorem [73-76]:

For superadditivity:

$$v(\{1\}) + v(\{2\}) \leq v(\{1,2\}) \tag{14}$$
$$v(\{1\}) + v(\{3\}) \leq v(\{1,3\}) \tag{15}$$
$$v(\{2\}) + v(\{3\}) \leq v(\{2,3\}) \tag{16}$$
$$v(\{1\}) + v(\{2,3\}) \leq v(\{1,2,3\}) \tag{17}$$
$$v(\{2\}) + v(\{1,3\}) \leq v(\{1,2,3\}) \tag{18}$$
$$v(\{3\}) + v(\{1,2\}) \leq v(\{1,2,3\}) \tag{19}$$

For convexity:

$$v(\{1,2\}) + v(\{1,3\}) \leq v(\{1,2,3\}) + v(\{1\}) \tag{20}$$
$$v(\{1,2\}) + v(\{2,3\}) \leq v(\{1,2,3\}) + v(\{2\}) \tag{21}$$
$$v(\{1,3\}) + v(\{2,3\}) \leq v(\{1,2,3\}) + v(\{3\}) \tag{22}$$

For balancedness:

$$v(\{1,2\}) + v(\{1,3\}) + v(\{2,3\}) \leq 2v(\{1,2,3\}) \tag{23}$$

In games with an empty Core, Summerfield & Dror's [18] approach is considered as described above. Recalling that the players' decisions in the first stage of the game are represented by $z_i \in \{0, 1\}$, we assume for simplicity that the decision cost during the first stage is $-c^1(z_i) = 0$; this could easily be generalised to include first-stage decision costs. In terms of the upper and lower payments $\overline{x_i}$ and $\underline{x_i}$, since $\overline{x_i}$ and $\underline{x_i} \in \mathbb{R}^n$ and we assume transferable utility games, then $\alpha_i \overline{x_i} + (1 - \alpha_i)\underline{x_i} = x_i$. This implies that $\overline{x_i}$ and $\underline{x_i}$ represent player i's income and costs, respectively, which form the coalitional values listed above. Accordingly, player i is confident about the influence that incomes or expenses might have on the final payoff. This will allow determining the upper and lower bounds that are necessary to use the confidence indexes, even when there is an empty Core and the grand coalition may form. Considering this, we solve (4), (5), and (6).

Another aspect is that, in reality, players might not have perfect information about each other's confidence indexes; hence, they might not know which coalitions the other players prefer. We therefore propose an alternative approach that combines the benefit of using probability distributions and the idea behind the confidence index. In this approach, we assume that each confidence index (α_i) follows a uniform distribution. This implies that each degree of confidence about the final payoff has the same probability, because none of the players knows anything about other players' confidence. We determine the Nash equilibrium (best strategy, coalition, and final payoff) for each player, randomly sampling 10,000 points from each distribution by solving (4), (5) and (6). This will help to better understand which project (coalition) prevails when players do not know the other players' confidence indexes. Furthermore, this will give an idea about the likelihood of coalition formation. To track the final results, we model a matrix that is shown in Fig. 2. In this matrix, player 1 chooses the rows, player 2 chooses the columns, and player 3 chooses the matrices.

$$
\begin{array}{c|ccc|ccc}
 & & \{\emptyset\} & & & \{2\} & \\
 & & z_2 = 0 & & & z_2 = 1 & \\
\hline
z_1 = 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
z_1 = 1 & 0 & 0 & 0 & x_i & x_i & 0 \\
\hline
 & & & z_3 = 0 & & & \\
 & & \{1\} & & & \{1,2\} &
\end{array}
\qquad
\begin{array}{ccc|ccc}
 & \{3\} & & & \{2,3\} & \\
 & z_2 = 0 & & & z_2 = 1 & \\
\hline
0 & 0 & 0 & 0 & x_i & x_i \\
x_i & 0 & x_i & x_i & x_i & x_i \\
\hline
 & & z_3 = 1 & & & \\
 & \{1,3\} & & & \{1,2,3\} &
\end{array}
$$

Fig. 2. Matrix for tracking best strategies / coalitions

4. Results

We first verify whether our games have a non-empty Core, by computing inequalities (14) to (23). The findings of this procedure are shown in Table 12.

Table 12
Test results for Superadditivity, Convexity, and Balancedness for every game

Games / Criterion	Superadditivity	Convexity	Balancedness	Type of Core
Game 1 – Chilean case	Yes	Yes	Yes	Non-empty
Game 2 – Scottish case	Yes	No	No	Empty
Game 3 – Chilean case with cost subsidisation	Yes	No	No	Empty
Game 4 – Scottish case with cost subsidisation	Yes	No	No	Empty

As can be seen above, only game 1 has a non-empty Core. We follow Branderburger & Stuart's [17] method to solve this game. For the rest of the games, we follow Summerfield & Dror's [18] approach as explained above.

4.1 Numerical results for game 1

Taking into account (3) and solving (11) to (13), we determine the Core for this game considering constraints (24) to (28), which are based on the coalitional values listed in Table 8, in order to comply with the coalitional rationality criterion and efficiency principle:

$$x_1, x_2, x_3 \geq 0 \tag{24}$$
$$x_1 + x_2 \geq 2.02 \tag{25}$$
$$x_1 + x_3 \geq 0.32 \tag{26}$$
$$x_2 + x_3 \geq 1.39 \tag{27}$$
$$x_1 + x_2 + x_3 = 4.29 \tag{28}$$

We therefore plot a triangle with barycentric coordinates as can be seen in Fig. 3, which shows the possible imputations that can be freely assigned to the players, which are inside the Core and comply with the two aforementioned criteria.

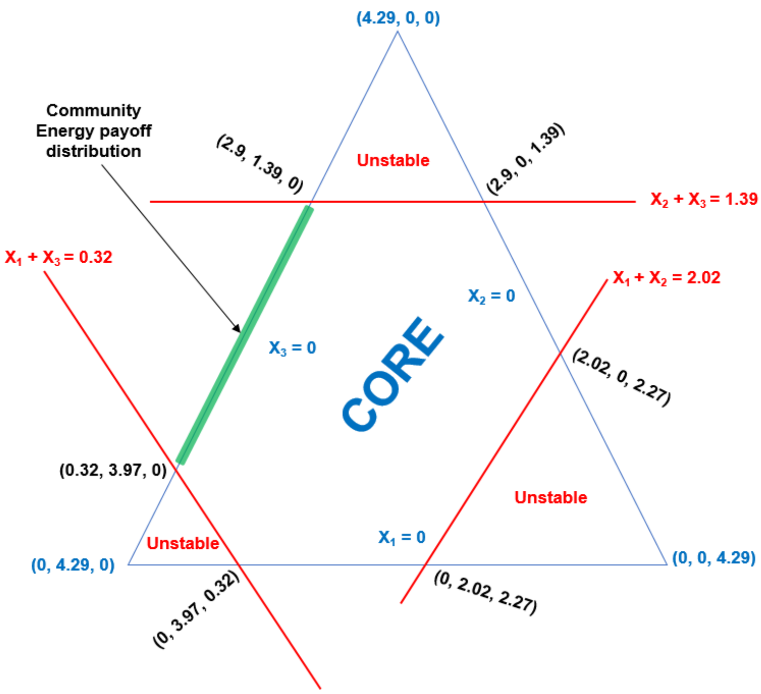

Fig. 3. Non-empty Core for Game 1 (amounts in thousands of USD)

These results are not straightforward. If players 1 and 2 block any participation (and payoff) for player 3 and decide to form coalition {1,2}, the worst acceptable payoff for them will be 0.32 and 1.39, respectively. Clearly, player 3 will have the incentive to participate in another coalition, as he receives zero. In the case of being involved in another coalition, the worst acceptable payoff for players 1 and 2 will be zero. Similarly, the best acceptable payoff for players 1 and 2 will be same in either coalition {1,2} or a different one. Hence, assigning a conservative confidence index for each player, which means that each player has a neutral payoff expectation, we determine the Nash equilibrium taking the payoffs shown in Fig.3 and solving (2), as noted in Table 13.

Table 13
Final results for Game 1 (rounded amounts in thousands of USD taken from Fig. 3.)

Strategies / Players	Player's possible payoffs			Player's confidence - α_i			Best strategy		
	1	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Best payoff forming {1,2}	2.9	4.0	0.0						
Worst Payoff forming {1,2}	0.3	1.4	0.0	0.5	0.5	0.5	{1,2}	{1,2}	≠ {1,2}
Best payoff forming another coalition	2.9	4.0	2.3						
Worst Payoff forming another coalition	0.0	0.0	0.3						

Forming coalition {1,2} implies that the strategy of being a consumer and/or producer of electricity by implementing a community energy project (CEP) is optimal, so we can say that the rest of the possible coalitions follow other options (No CEP). Accordingly, as can also be seen in Fig. 4, the Nash equilibrium is (CEP), (CEP), and (No CEP) for players 1, 2, and 3, respectively.

Player 3: CEP

Player 1 \ Player 2	CEP	No CEP
CEP	1.6 2.7 0.0	1.6 2.0 0.0
No CEP	1.5 2.7 0.0	1.5 2.0 0.0

Player 3: No CEP

Player 1 \ Player 2	CEP	No CEP
CEP	**1.6 2.7 1.3**	1.6 2.0 1.3
No CEP	1.5 2.7 1.3	1.5 2.0 1.3

Fig. 4. Nash equilibrium for Game 1 (amounts in thousands of USD)

In Fig. 4, player 1 chooses the rows, player 2 chooses the columns, and player 3 chooses the matrices. It is important to notice that even when the confidence index changes for all players, the resulting Nash equilibrium will be the same in this case.

4.2 Numerical results for games 2, 3, 4, and simulation

4.2.1 Games 2, 3, and 4

We solve (4), (5), and (6), and modify each confidence index, one at a time, in order to determine the possible Nash equilibria given the specific confidence indexes. The findings are shown in Tables 14, 15, and 16.

Table 14
Game 2 - Intervals for players' confidence and corresponding Nash Equilibrium

Players' confidence	Nash Equilibrium
$0.401 \leq \alpha_1 \leq 1$ $0.401 \leq \alpha_2 \leq 1$ $0.000 \leq \alpha_3 \leq 0.487$	Community energy scenario
$0.943 \leq \alpha_1 \leq 1.000$ $0.953 \leq \alpha_2 \leq 1.000$ $0.488 \leq \alpha_3 \leq 1.000$	Distributed generation scenario
$\alpha_1 = 1.000$ $0.000 \leq \alpha_2 \leq 0.952$ $0.488 \leq \alpha_3 \leq 1.000$	Base scenario {1,3}
$0.000 \leq \alpha_1 \leq 0.942$ $\alpha_2 = 1.000$ $0.488 \leq \alpha_3 \leq 1.000$	Base scenario {2,3}

Table 15
Game 3 - Intervals for players' confidence and corresponding Nash Equilibrium

Players' confidence	Nash Equilibrium
$0.086 \leq \alpha_1 \leq 1$ $0.086 \leq \alpha_2 \leq 1$ $0.000 \leq \alpha_3 \leq 0.465$	Community energy scenario
$0.503 \leq \alpha_1 \leq 1.000$ $0.802 \leq \alpha_2 \leq 1.000$ $0.466 \leq \alpha_3 \leq 1.000$	Distributed generation scenario
$\alpha_1 = 1.000$ $0.000 \leq \alpha_2 \leq 0.801$ $0.466 \leq \alpha_3 \leq 1.000$	Base scenario {1,3}
$0.000 \leq \alpha_1 \leq 0.502$ $\alpha_2 = 1.000$ $0.466 \leq \alpha_3 \leq 1.000$	Base scenario {2,3}

Table 16
Game 4 - Intervals for players' confidence and corresponding Nash Equilibrium

Players' confidence	Nash Equilibrium
$0.069 \leq \alpha_1 \leq 1$ $0.069 \leq \alpha_2 \leq 1$ $0.000 \leq \alpha_3 \leq 0.487$	Community energy scenario
$0.906 \leq \alpha_1 \leq 1.000$ $0.930 \leq \alpha_2 \leq 1.000$ $0.488 \leq \alpha_3 \leq 1.000$	Distributed generation scenario
$\alpha_1 = 1.000$ $0.000 \leq \alpha_2 \leq 0.929$ $0.488 \leq \alpha_3 \leq 1.000$	Base scenario {1,3}
$0.000 \leq \alpha_1 \leq 0.905$ $\alpha_2 = 1.000$ $0.488 \leq \alpha_3 \leq 1.000$	Base scenario {2,3}

Given that coalitions $\{1\}, \{2\}, \{3\}$, and the empty coalition $\{\emptyset\}$ have the same coalitional values (equal to zero), we assume an empty solution for the first stage, namely, the decisions $z_1 = z_2 = z_3 = 0$ or $\{\emptyset\}$, if the Nash equilibrium is one of these coalitions. It is also clear that if the players' confidence indexes do not meet one of the intervals, the solution will be $z_1 = z_2 = z_3 = 0$ or $\{\emptyset\}$.

4.2.2 Simulation

As explained above, we also simulate uncertainty about confidence indexes by considering 10,000 solutions to (4), (5), and (6), randomly and independently drawing confidence indexes from uniform distributions with support [0,1]. We then obtain the percentage of specific Nash equilibria (strategies/coalitions) out of the total number of cases/iterations, which are shown in Table 17.

Table 17
Nash Equilibria as a percentage out of the total number of iterations.

Strategies or coalitions / Games	Game 2	Game 3	Game 4
No relation among the players - $\{\emptyset\}$	82.74%	56.27%	56.89%
Community energy scenario	17.08%	38.63%	42.69%
Distributed generation scenario	0.18%	5.10%	0.42%

According to Table 17, even when there is no knowledge among the players about people's confidence, there is an opportunity for implementing community energy projects in both countries, considering games 2, 3, and 4.

We also determine the minimum thresholds necessary for obtaining a particular coalition as solution, in terms of payments (x_i) and confidence indexes for each player and game. These are presented in Table 18, and although they are naturally sensitive to the sample size, they do show that even relatively low confidence levels can be enough for a community energy project to emerge as an equilibrium solution.

Table 18
Minimum threshold observed in 10,000 iterations, in terms of x_i and α_i (rounded amounts in USD)

Coalition	Player / Games	Game 2	Game 3	Game 4
Community energy scenario	Player 1	$x_i = 2.55$ $\alpha_i = 0.401$ $1 - \alpha_i = 0.599$	$x_i = 0.08$ $\alpha_i = 0.086$ $1 - \alpha_i = 0.914$	$x_i = 4.6$ $\alpha_i = 0.069$ $1 - \alpha_i = 0.931$
	Player 2	$x_i = 7.10$ $\alpha_i = 0.401$ $1 - \alpha_i = 0.599$	$x_i = 8.57$ $\alpha_i = 0.086$ $1 - \alpha_i = 0.914$	$x_i = 1.19$ $\alpha_i = 0.069$ $1 - \alpha_i = 0.931$
Distributed generation scenario	Player 1	$x_i = 28.18$ $\alpha_i = 0.945$ $1 - \alpha_i = 0.055$	$x_i = 1.59$ $\alpha_i = 0.503$ $1 - \alpha_i = 0.497$	$x_i = 6.41$ $\alpha_i = 0.907$ $1 - \alpha_i = 0.093$
	Player 2	$x_i = 3.75$ $\alpha_i = 0.953$ $1 - \alpha_i = 0.047$	$x_i = 3.9$ $\alpha_i = 0.802$ $1 - \alpha_i = 0.198$	$x_i = 7.45$ $\alpha_i = 0.931$ $1 - \alpha_i = 0.069$
	Player 3	$x_i = 2045.93$ $\alpha_i = 0.566$ $1 - \alpha_i = 0.434$	$x_i = 16.93$ $\alpha_i = 0.466$ $1 - \alpha_i = 0.534$	$x_i = 58.77$ $\alpha_i = 0.489$ $1 - \alpha_i = 0.511$

5. Discussion and recommendations

5.1 Discussion of the games and their results

In relation to game 1 (Chilean case shown in Fig. 3, Table 13, and Fig. 4), it is important to note that this game has a non-empty Core and no cost subsidisation is considered. Based on the results above, player 1 (the low-medium income residential customer) and player 2 (the high income residential customer) will form a coalition in order to carry out a community energy project, which is represented by coalition $\{1,2\}$. This strategy is the most profitable for them, under our assumptions. Player 3 (the electricity distributor) would not be interested in participating in such coalition $\{1,2\}$, as it might be offered a payment equal to zero (and then blocked to do so). If the distributor were offered a better payoff/payment, e.g., $x_3 = 1.43$ (with a Core $C(v) = \{x_1, x_2, x_3 \in \mathbb{R}^3 : x_1 + x_2 + x_3 = 4.29,\ x_1 = 1.43,\ x_2 = 1.43,\ x_3 = 1.43\}$), such payoff distribution would not be preferred by both residential electricity customers, as there is another (better) option for them. Consequently, this would motivate blocking measures and then the community energy coalition formation, leaving the distributor aside.

In game 2 (Scottish case shown in Tables 14, 17, and 18), no costs subsidisation is considered and it has an empty Core, so we adopt Summerfield & Dror's [18] solution approach. Here, the community energy coalition requires a lower income to cover the costs, as the minimum required confidence indexes to form coalition $\{1,2\}$ is relatively low ($\alpha_i \geq 0.401$). Hence, as long as both residential electricity customers have that level of confidence and the supplier is slightly pessimistic about the results of the game or negotiation process ($0 \leq \alpha_3 \leq 0.487$), the best strategy (represented by the Nash equilibrium) for all players will be the implementation of a community energy project. On the other hand, if the supplier is more confident about the results of the negotiation process ($0.487 \leq \alpha_3 \leq 1.000$) and both residential electricity customers are also more confident about the results, leaving the uncertainty aside, the best strategy will be the implementation of a net billing project. This might be also interpreted as follows: the less uncertainty (alternatively, the more confidence) you have, the more attractive the traditional electricity provision scheme is. This can be seen in all games, especially when a regular utility contract is the best strategy for all players (coalitions $\{1,3\}$ and $\{2,3\}$ in Table 14). Here, there is no uncertainty for both residential customers because they have to pay their bill every month, which is received by the supplier. At the same time, due to both residential electricity consumers' confidence, the supplier can participate in the coalition even when it is moderately, very, or completely confident that it can extract this revenue. The results of our probabilistic analysis also show that there are opportunities for community energy initiatives, as shown in Table 17. The successful cases in which the best strategy for all players is the implementation of community energy projects reached 17.08%, a percentage that is higher that of distributed generation projects (0.18%). As it happens, community energy initiatives are relatively popular in Scotland, compared to other types of citizen participation, so although our model is simple, it does go some way in explaining reality.

Considering games 3 and 4 (Chilean and Scottish case, respectively), both games present an empty Core but in these cases, a cost subsidy is considered. As can be seen in Table 15 (Chilean case), the required confidence for implementing community energy projects (represented by coalition $\{1,2\}$) reaches a very low level for both residential customers ($\alpha_i \geq 0.086$). At the same time, the distributor may be pessimistic about the results of the game or negotiation process ($0 \leq \alpha_3 \leq 0.465$) but there would be a favourable environment for conceiving community-led projects, as the best strategy for all players is forming coalition $\{1,2\}$. The same feature can be seen in Table 16 (Scottish case), where the required confidence for forming coalition $\{1,2\}$ is also very low for both residential consumers ($\alpha_i \geq 0.069$) and, again, the supplier may be pessimistic about how well he can perform within the bargaining process ($0 \leq \alpha_3 \leq 0.487$) but the best strategy for all incumbents will be carrying out a community energy project. In this sense, according to all possible solutions of these 2 games, including those solutions where having a regular utility contract (represented by coalitions $\{1,3\}$ and $\{2,3\}$ in Tables 15 and 16) is the best strategy, we notice that the less uncertainty (alternatively, the more confidence) one has, the more traditional the electricity provision scheme is preferred. From our probabilistic results shown in Table 17, we can see a remarkable percentage of community energy equilibria (38.63% and 42.69% for the Chilean and Scottish case, respectively), in comparison with distributed generation strategies (5.10% and 0.42% for the Chilean and Scottish case, respectively). This is not entirely surprising, as the costs of community energy have been decreased significantly.

Comparatively speaking, the confidence index for each scenario and player in games 2 and 4, which are presented in Tables 14 and 16 for the Scottish case, is influenced by a cost subsidisation under the community energy scenario. This effect implies a significant reduction on the required confidence index for both residential customers, in order to have a community energy initiative as solution (from $0.401 \leq \alpha_i \leq 1$ to $0.069 \leq \alpha_i \leq 1$ for both players). In relation to the distributed generation scenario, there is also a reduction in the required confidence index for the same incumbents, but by a lower amount (from $0.943 \leq \alpha_1 \leq 1$ and $0.953 \leq \alpha_2 \leq 1$ to $0.503 \leq \alpha_1 \leq 1$ and $0.802 \leq \alpha_2 \leq 1$, respectively). Although those significant reductions in the confidence indexes came from one scenario (community energy), the possible equilibria in the game were altered. This is interesting because a modification of costs structures affects the possible equilibria, and therefore the probability of a specific coalition forming. This can be noted in our simulation (shown in Table 17) where a cost subsidisation is considered. For example, in the Scottish case, the successful cases in which implementing community energy projects was the best strategy for all players increased from 17.08% in game 2 to 42.69% in game 4. We also notice that the likelihood of having a net billing schemes as a solution is almost zero (0.42%), which is consistent with the current market context.

5.2 General remarks and recommendations

Taking into account all of the above, recalling the research questions revealed before, we note some important elements. First, an appropriate payoff distribution between both residential customers can assure stability and, therefore, long-lasting coalition formation, as no attractive option would influence any change in the coalition or project. Second, the negotiation between both residential consumers will be especially crucial, given that without a successful bargaining process the emergence of the community energy project (coalition formation) might not occur. Third, the interaction between the residential customers' negotiation power and that of the distributor/supplier is critical because both residential consumers should be able to operate and run the business without any involvement from the distributor/supplier. This seems contradictory in the current context where distributors and/or suppliers play a major role in the electricity markets, especially at an end-user level. We do not want to imply that our results suggest a total exclusion of distributors, but rather suggest that they may be better placed in other supporting roles for community energy projects, such as ancillary services for small-scale projects. Thus, the regulatory environment should favour market freedom and free access to other (potential) incumbents, namely, community energy projects, promoting equality in terms of negotiation and avoiding any market power exercise. Nevertheless, it is also true that promoting more flexibility and adaptability for distributors/suppliers will be necessary in case of a wider deployment of community energy projects, as this would potentially reduce their market share. Fourth, one of the most crucial assumptions we make is that residential customers can afford any level of costs, which is particularly important for games 1 and 2. This might not be true unless customers have access to a saving scheme or direct subsidies before entering the business, or simply have the money to do so. More work is needed to explore the impacts of credit constraints and policies to alleviate these. Finally, there are other factors that are not considered in this paper; for example, the specific terms and conditions for public or private funding, how establishing PPAs or other contracts would affect the economic-strategic viability, and other costs that might be relevant (design & engineering, system infrastructure - metering, lines, and other equipment -, legal, first buyer, operational, marketing, and so on). We also do not consider carbon reduction incentives. Our approach based on biform games could take these into account. For instance, PPAs, which represent a higher income for community energy initiatives in case of having electricity (surpluses) to export through the grid, would move the conclusions towards more stability and higher economic-strategic viability for community energy initiatives. Carbon incentives would work in the same way. On the contrary, considering other costs would move the conclusions in the opposite direction. Given that each project or scheme has its own particularities and complexities, we consider a comparative base in terms of income and costs as realistic and uniform as possible. This is why, for example, solar PV retail investment costs and overnight costs are considered for the net billing scheme and community energy project, respectively. By taking these costs into account, we can better represent payoffs so that the decision can be seen as a decision on the implementation of turnkey projects with a comparative base. Therefore, any additional cost can be added without reducing model transparency and increasing computational cost. Further research can deal with this situation, for instance, through the combination of more advanced optimisation models and biform games that consider other costs. Based on the above, we can say that our results show consistency with the current situation in Scotland and Chile, where community energy projects have been promoted in the former and net billing projects in the latter, even when that is not necessarily optimal for residential customers in Chile [12]. This means that, from an economic-strategic perspective considering our mild assumptions, community energy projects can be a viable and competitive option to produce energy for residential customers, which addresses the research questions listed above.

Our findings are also aligned with a variety of empirical studies. For instance, Walker [26] states that "local income and regeneration" is one of the key incentives for community ownership. Based on a survey, Seyfang et al. [25] notice that the economic objectives are one of the most important aspects for UK community energy groups. For a group of case studies, Hicks & Ison [22] note that "financial benefits for shareholders and/or community" is a leading motivation. Ebers Broughel & Hampl [37] based on two large-scale representative surveys performed in Austria and Switzerland, show the existence of potential investors who are willing to invest between 1,000 and 10,000 CHF/EUR in community energy projects. Brummer [24] highlights that "economic benefits" is one of the most cited categories for a set of UK-based investigations. On the other hand, for the same set of studies notices that the most cited barrier is "lack of resources" (funding, time, and expertise). Nolden [43] shows the challenges for gathering financial resources. As noted above, the specific terms and conditions of private and/or public funding are not accounted in our approach. Berka et al. [46] notice that community energy projects face higher costs, longer project development times, and higher risks, which is influenced by six facets of an organisation or project. None of these six facets are accounted in our approach. Abada et al. [47] establish that even when it is possible a value creation by community-led coalitions, there is no guarantee that they are viable, as some members would exit the project or coalition. Again, there are several factors that play a role in this case: firstly, as mentioned beforehand, this study considers a project that would be more related to the definition of distributed generation shown above. Secondly, there are also other game theory tools that are taken into account in this study. Finally, the methodology and modelling are different.

All the above does not necessarily mean that our results have to be strictly aligned to other trends in other markets, as there are other factors that may have not been taken into account in our games, as shown above. For example, costs, other empirical or legal definitions of projects, technologies and energy sources availability, among others, may influence our results and their alignment to other trends in energy markets. More research could address this.

Another key element is the role of the confidence index and its practical meaning. As shown before, this index reflects players' confidence on how well they could do within the game, i.e., how large a fraction of the coalitional value they could capture. For games with an empty Core, we adapt this so that the confidence index reflects players' expectations on the influence that changes in revenues or expenses might have on the final payoff. With this slight modification, we determined the upper and lower payoff bounds, applied the corresponding confidence indexes, and calculated the final payoffs, even with an empty Core, as well as the formation of the grand coalition. Conceptually speaking, these approaches have the same aim, i.e., obtaining the final expected payoff. In both cases, a high confidence index represents an optimistic view about the final payoff. In practice, this can have a number of reasons; players, for instance, may have an optimistic view of their own bargaining power, or attach a high value to particular project benefits. Moreover, the confidence index can include a component related to uncertainty. When a player has a high confidence index, this can imply that that player has less uncertainty about getting a particular payoff. This is why, in our results, higher confidence indices lead players to prefer traditional electricity provision schemes. Further research is needed to explore the best way to accurately determine such index in the real world. As the confidence index is related to people's beliefs and is beyond the financial conception of uncertainty, we think that social sciences, like sociology or psychology, may have a say on this matter.

Again, following our mild assumptions, the findings presented above support the idea that community energy projects can provide stability to their members and be economically-strategically feasible or viable and competitive in comparison to other schemes, such as net billing (or distributed generation) schemes. According to our games and their results, the factors that determine the relative success of community energy projects, and then the relative success of the other two schemes, can be summarised as follows:

a) Negotiation power and stability; if the players within a (potential) coalition can agree on distributing the payoffs in a way that all of them are satisfied and therefore their intention is to collaborate and remain inside the coalition, then that coalitional formation should be prioritised. However, the negotiation power can make the difference in terms of implementing a particular scheme (forming a particular coalition). For example, as shown above, both residential customers may block the distributor and then form the community energy coalition.
b) Confidence; the players' confidence affects the coalitional formation as revealed beforehand. For example, in games 2, 3, and 4, it can be seen that the distributor/supplier's confidence influences the formation of the community energy coalition, when it reaches any value under a certain threshold.
c) Market conditions and payoff estimation; our calculations are based on the determination of income and expenses, and therefore coalitional payoffs. These values, at the same time, are based on market data like energy injection and consumption rates, overnight costs, investment costs, interest rates, etc. Any different payoff estimation may influence the coalition formation shown in this work. One extreme example of this could be a situation where both net billing and community energy initiatives have the same payoffs to be weighted by the confidence index. Here, the coalition formation would be entirely affected by the players' negotiation power.

Based on all the aforementioned elements, some recommendations can be given:

1. Focus on community energy schemes instead of others, if a higher citizen participation in energy production is desired.
2. Evaluate the provision of long-term financial arrangements, considering the corresponding compensation or recovering mechanisms, in order to improve access to community energy projects. This may include promoting PPAs and other contracts that can improve a project's income generation and the recoverability of private/public funding.
3. Promote stronger collaboration amongst people in order to facilitate the formation of stable coalitions. In this sense, sharing/distribution rules based on biform games might be useful.
4. Define explicit public policies and goals related to the above-mentioned points, in order to have measurable and verifiable milestones of progress.

We finally highlight that our examples based on biform games appropriately represent the community energy emergence problem, as it simultaneously models their non-cooperative and a cooperative stages. Biform games are therefore more realistic and useful tools than conventional one-stage approaches. As a counterfactual, for instance, if only the cooperative side of the problem is addressed, by using the Core or the Shapley value, the outcome would only give information about how players should distribute the payoff within a specific coalition, without being able to quantify the level of competition between different types of schemes. Conversely, without modelling a cooperative stage, results about the economic feasibility of community energy projects may be overly optimistic, as the need for a feasible distribution of payoffs is neglected. Consequently, we think of our approach as a complement that contributes to the existing literature.

6. Conclusions

This paper proposes a simple but novel approach for demonstrating the economic-strategic viability of community energy projects, which adapts biform game theory to energy markets. Given the increasing importance of the community energy sector, we see many opportunities to use biform games, which are still relatively unknown in comparison with other game theoretical tools. Using these tools will help to better understand the underlying economics of the sector.

Using publicly available real-world data, we model simple biform games for Chile and Scotland. Under mild assumptions, it is possible to see the economic-strategic viability and competitiveness of a wider implementation of community energy projects in both countries, as it appears to be the best strategy for residential customers. Consumer confidence is crucial, unless a significant gap between incomes and costs exists (e.g., because of subsidies), in which case the importance of that confidence is reduced. Our examples also uniformly show that the less uncertainty (alternatively, the more confidence) consumers have, the more traditional their electricity provision is likely to be.

The results shown in this work are in agreement with the current Scottish situation in community energy development, and they are useful for other countries, like Chile, that are trying to increase citizen participation in energy production. Fostering a community energy sector could be especially critical in developing countries like Chile, where this sector is still incipient while political attention is predominantly focused on other mechanisms, such as net billing. Community energy projects could contribute to the efforts to halt climate change, increasing the renewable energy participation in electricity markets, strengthening local economies, and improving the quality life of communities. Of course, there are challenges, especially in terms of affordability. However, as long as communities can be enabled to enter the business, their economic-strategic viability seems promising.

More research about the economics of the community energy emergence and more knowledge about other aspects that might be crucial to this sector are necessary, especially those matters that are not accounted in this analysis. With this paper, we attempt to encourage further work to do so.

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